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Stable Homogeneous Microdischarge at Atmospheric Pressure between a Flat Cathode and Point Anode

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Abstract—Conditions of stable operation of a homogeneous glow microdischarge in air at atmospheric pressure between a flat cathode and point anode are established and realized at interelectrode gap widths within ~1–30 μm and discharge currents within from ~10^{-4} to 1 A.

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In recent years, much interest has been devoted to studying homogeneous weak-current microdischarges in atmospheric air, in which case the neutral gas heating is insignificant and the deposited electric energy is spent mostly on the excitation and ionization of plasma-forming gas molecules [1, 2]. However, as the gas pressure increases, the discharge becomes less homogeneous and the main role is played by sharply inhomogeneous and nonstationary forms of breakdown that lead to the development of various instabilities [1]. On the other hand, one of the most characteristic features of low-pressure discharge is its remarkably stationary and homogeneous operation. Due to the nonlocal character of the electron-distribution function (EDF), the electron-concentration profile in this discharge is dome-shaped irrespective of the spatial distribution and the mechanism of energy deposition [2]. Since the criterion of EDF nonlocality is determined by the condition $pL < 10$ cm Torr [2], where p is the room-temperature (300 K) pressure and L is the interelectrode gap width, this criterion at high pressures corresponds to small (10–100 μm) distances. This agrees with the experimental data, according to which the optimum conditions of glow discharge initiation and operation correspond to the region of minimum on the Paschen curve (Stoletov point)—i.e., to voltages within $U \sim 200$–350 V and the values of product $pL \sim 0.5$–5 cm Torr. At high pressures, this corresponds to micron distances, at which a self-sustained autonomous positive column is absent (since there is no "room" for its formation [1]) and almost all applied voltage drops on the cathode layer so that the current–voltage (I–U) characteristic of discharge has an ascending shape. At the same time, the initiation of more extended discharges must be unavoidably accompanied by the formation of a positive column with descending I–U curve. This leads to the development of thermal instabilities and breakage of stable discharge operation [1].

Thus, in order to obtain a stable homogeneous discharge at high pressures, it is necessary to provide conditions under which parameter pL would fall in the region of minimum on the Paschen curve. In this case, the ascending I–U curve will favor stable discharge operation and nonlocal EDF will ensure homogeneity of the discharge.

In this work, we have established and realized these conditions for microdischarge in open air at atmospheric pressure in the gap between a flat cathode and point anode at short interelectrode distances $L \sim 1$–30 μm and discharge currents within from 10^{-4} to 1 A.

In order to control the interelectrode gap width within a small interval (1–30 μm), we have used a cantilever system with a 330-mm-long lever, one end of which could rotate about the axis with bearings and the other could be driven by a micrometric dial screw. The point electrode holder was fixed on the level at a distance of 33 mm from the axis of rotation, so that the dial scale division corresponded to 1 μm. The gap was initially closed (shorted) and then opened slowly so as to detect the point of zero dc current passage (zero gap), after which any desired gap width could be set by rotating the micrometric screw in one direction.

Preliminary investigations of microdischarge in open air at atmospheric pressure showed that dc currents on a level of ~10 mA in most cases lead to strong heating and erosion of the electrodes, which lead to significant and irreversible changes in measured parameters. For this reason, the subsequent experiments were performed in a quasi-pulsed regime of discharge. The discharge had power supplied to it from a source of single voltage pulses with a shape close to a sinusoid half-period with a duration of ~25–100 ms, which was connected to the interelectrode gap via a limiting resistor (364, 44.6, or 2.74 kΩ). The voltage

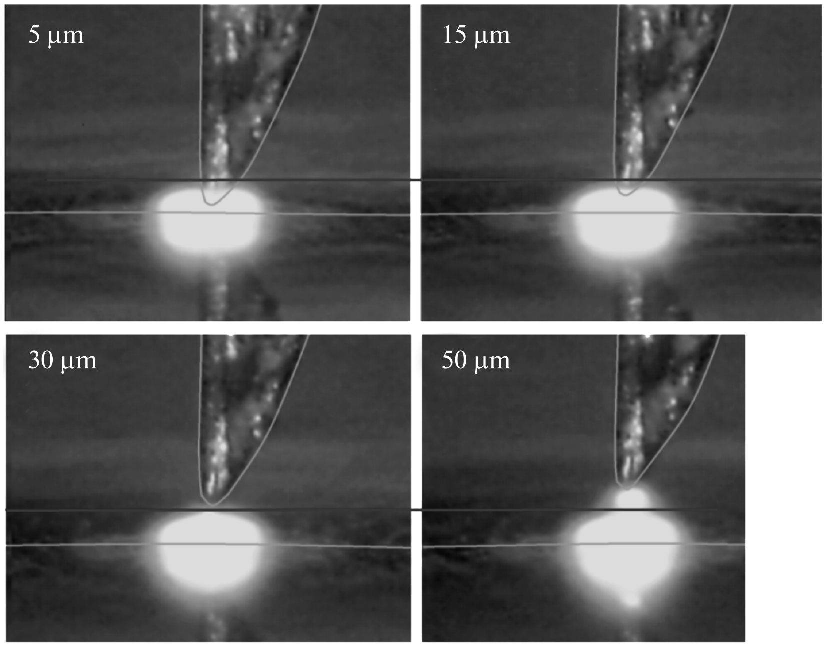

Fig. 1. Discharge between a flat cathode and point anode (with a tip curvature radius of 7 μm) at a current of 1 mA and various interelectrode distances.

was taken from a 15-Ω (or 55-Ω) resistor, through which a capacitor bank (300 or 900 μF) was discharged via a 0.2-H coil with the internal resistance of 6 Ω after being charged to 5 kV. The main parameters of discharge were determined with the aid of an oscilloscope, which measured voltage waveforms on the gap and on the limiting resistor via 1 : 1000 voltage dividers with 10-MΩ input resistance. The *I*–*U* curves of discharge were constructed upon averaging over several waveforms.

At the first stage, we have studied the standard discharge between flat cathode and point anode with a very large curvature radius (from 10 mm to several meters) compared to the discharge length. The results showed that the minimum voltage of discharge with steel cathode in the entire interval of currents (5–50 mA) corresponds to a gap width of about 30 μm in contrast to a value corresponding to the minimum of the room-temperature Paschen curve (7–10 μm [1]). It should be noted that, since a flat cathode was used in all the experiments under consideration, a normal discharge was observed in all intervals of discharge current, so that an increase in the current was accompanied by growth in the cathode-spot area [1]. This behavior is indicative of a corresponding decrease in the gas density and increase in the gas temperature in the zone of discharge (related to a high normal current density of the glow discharge at atmospheric pressure) and confirms the possibility of their measurement by the proposed method. In a planar gap with widths near the minimum of the Paschen curve and on its left branch (15 μm and below), the discharge behavior is ambiguous and these measurements would be difficult to perform because of a strong influence of the gap nonuniformity and surface roughness, which lead to multiple breakdowns even at voltages below 330 V.

In order to solve the tasks of this investigation, we have used a discharge between a flat cathode and point anode in the form of a sharp needle with a small tip curvature radius. Distance L_0 between the flat cathode and point anode was set below the value ($L_{\min}$) corresponding to the minimum of the Paschen curve. For this reason, gas breakdown voltage U and the discharge coupling to the anode correspond to the minimum of the Paschen curve ($U = U_{\min}$, $L = L_{\min}$); i.e., discharge is initiated above the point tip at $L_{\min} > L_0$, as if the discharge would control its own length so that it would correspond to stable operation in the region of the minimum ($L_{\min}$) of the Paschen curve. As a result, the voltage drop on the discharge gap has a constant value (on the order of $U_{\min}$), which weakly depends on the gap width and gas pressure. In addition, this technical result is achieved due to the fact that the electric capacitance of the given electrode configuration is much smaller than that in the case of two flat electrodes. All these factors lead to increasing stability of discharge with respect to spark initiation (bifurcation to a regime of *RC* oscillations) at a current of several milliamperes or below and small discharge gap widths.

The results of experiments showed that the gas breakdown and discharge with a point anode (at a curvature radius up to ~25 μm) in the vicinity of the minimum of the Paschen curve exhibit the following specific features. On the left of this minimum, both the breakdown and negative-glow (NG) plasma appear above the point tip and the field and NG are distorted by the penetrating point (Fig. 1). For this reason, the

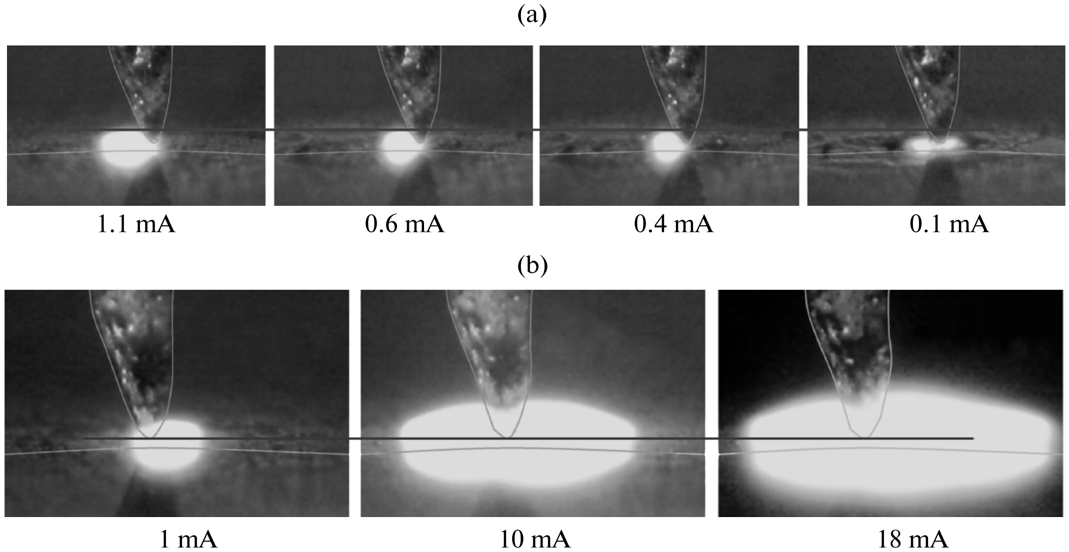

Fig. 2. Dynamics of microdischarge at (a) a constant gap width of 10 μm and the current varied from 1.1 to 0.1 mA and (b) a constant gap width of 15 μm and the current varied from 1 to 18 mA.

voltage drop is almost constant (300–310 V) and weakly depends on the gap width and gas pressure. As the interelectrode distance is increased above 30 μm, a positive column begins to form (Fig. 1) and the voltage drop on the discharge gap increases. Although, as the interelectrode distance approaches 1 μm, the discharge between two flat electrodes is unstable even at a small current, a small interelectrode capacitance allows relatively stable glow discharge with normal voltage drop to be readily obtained even at currents below 1 mA (Fig. 2a). As the discharge current was decreased from 1.1 to 0.3 mA, the discharge length and voltage drop remained almost unchanged. However, for greater variations of the discharge current (1–18 mA), this behavior was not observed (Fig. 2b).

Figure 2b shows that, as the discharge current is increased, the area of the glow region grows in almost direct proportion, which corresponds to a normal glow discharge at approximately equal current density [1]. Judging from the NG region size, it is possible to approximately estimate the current density in the near-cathode region of discharge. Data of video monitoring clearly show that the NG region size depends on the discharge current and amounts to ~100 μm at 1 mA, ~340 μm at 10 mA, and ~440 μm at 18 mA with the corresponding current densities being 0.1, 0.086, and 0.092 A/mm^2. Deviations from the linear growth of the spot on the flat cathode can be explained by asymmetric shape of the spot and by heating of the gas.

Thus, the results of our experiments showed that the discharge between flat cathode and point anode (with a strongly inhomogeneous field) at small interelectrode distances (5–30 μm) represents a normal discharge with an almost constant voltage drop of 300–320 V. At a discharge current of about 0.1 mA, the passage to unstable discharge was sometimes observed in the form of sharply initiated and quenched sparks (Fig. 2). This transition probably explains an increase in the discharge voltage (~20 V) that was observed in the *I–V* curve prior to termination of the current.

In conclusion, we have established and realized the conditions of stable operation of a homogeneous glow microdischarge in air at atmospheric pressure between a flat cathode and point anode at interelectrode gap widths within ~1–30 μm and discharge currents within from ~10^{-4} to 1 A.

REFERENCES

1. Yu. P. Raizer, *Physics of Gas Discharge* (Intellekt, Moscow, 2009) [in Russian].
2. A. A. Kudryavtsev, A. S. Smirnov, and L. D. Tsendin, *Physics of Glow Discharge* (Lan', St. Petersburg, 2010) [in Russian].

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